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Ferrite Permeability Measurements: Method and Results

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Results of dielectric permittivity measurement for several ferrites was presented in [1]. Knowing frequency behavior of this parameter can help in designing a kicker with relatively short rise time, required for the NOVA project at FNAL. Similar measurement should be made to find ferrite permeability. Knowing both parameters will help to choose proper material for the device.

I. Method Description

A scheme used for measurements is shown in Fig. 1. Here L is the inductance of a coil made with the use of a ferrite sample, resistor R2 represents an equivalent loss resistance of the ferrite, capacitance C2 is an input capacitance of a measurement device.

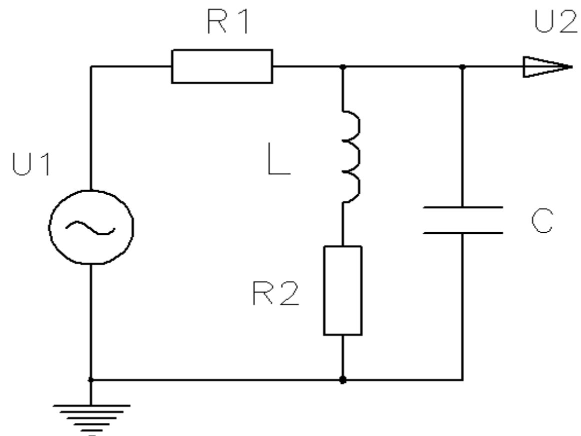


Fig. 1: Inductance measurement scheme.

Transfer function of this circuit Tr = U2/U1 is written below:

$$Tr(\omega) := \frac{\left[R2\cdot(R1+R2)+\omega^2\cdot L^2\right]+j\cdot\omega\cdot\left[L\cdot R1-C\cdot\left(\omega^2\cdot L^2\cdot R1+R1\cdot R2^2\right)\right]}{R2\cdot(R2+2\cdot R1)+\left(R1-\omega^2\cdot L\cdot C\cdot R1\right)^2+\omega^2\cdot\left(L^2+C^2\cdot R1^2\cdot R2^2\right)}$$

It is important to include the capacitance C in the circuit because the existing samples of ferrite material (toroids) have such a size that even with a one-turn winding their inductance can be high enough to result in onset of a parallel resonance in the frequency range of interest (0.2 – 20 MHs). Without taking into the account this resonance, the measurement data can be interpreted in a wrong way. As it was shown in [1], a value of the capacitance is ~ 14 pF.

The sample coil is made by employing a one-turn distributed primary winding using a ring-shaped ferrite sample. The winding is made in a way that makes the stray field inductance quite low. The inner diameter of all rings is 62.95 mm (~2.5”); the outer diameter is 101.6 mm (~4.0”); the width of the ring is ~19.25 mm (a bit more than 3/4”). The height of the ring is 25.4 mm (1”). This makes the cross-section area of the rings S = 489 mm^2. Uncertainties of the dimensions for all the measured rings are within 1%.

Fig. 2 shows some photos of the coil.

Fig. 2: Ferrite permeability measurement setup

To make firts estimate of the system response, we will accept that the value of the inductance is of the order of ~1 μH and R1 = 148 Ohm, as it was in [1]. Fig. 3 below shows the amplitude and the phase of the transfer function as a function of the frequency ω in the case when R2 = 0 (no losses).

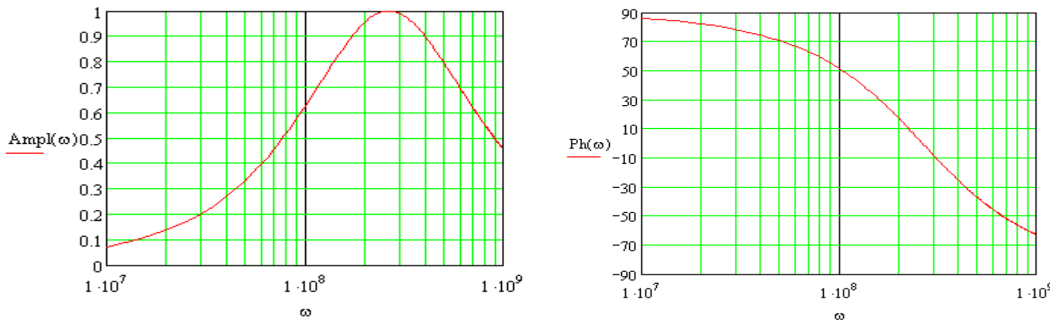
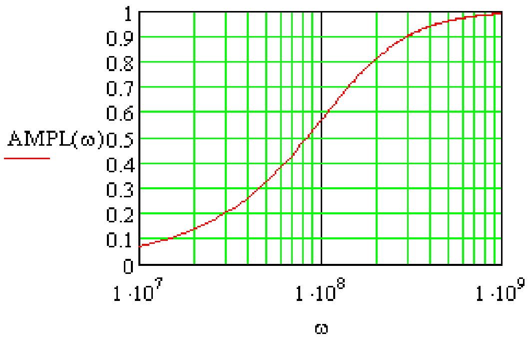


Fig. 3: Transfer function with R2 = 0

The behavior of the transfer function can be explained the next way:

- At low frequency, the impedance associated with the capacitance C is high and the impedance associated with the inductance L is low. In this case, the current through the inductance is defined by the resistance R2 and the output voltage is defined by the inductive impedance; the phase is close to 90°.
- As the frequency increases, the amplitude of the transfer function increases until the resonance point ω0 = 1/√(LC) is reached. For the chosen parameters, this point is $\omega = 2.7*10^8\ s^{-1}$ (f = 43 MHz). With the inductance higher than ~ 2 μH, the measurement setup and the data interpretation method ought to be more complicated. The impedance of the resonance LC circuit is infinite if R2 = 0, so the amplitude of the transfer function at this frequency is 1.0. The phase at this point is “zero”.
- As the frequency increases beyond the resonance point, the amplitude drops due to increased conductivity of the capacitance C. Phase becomes negative and approaches -90° at high frequency.

Fig. 4 shows, for comparison, corresponding graphs without taking into the account the capacitance C.



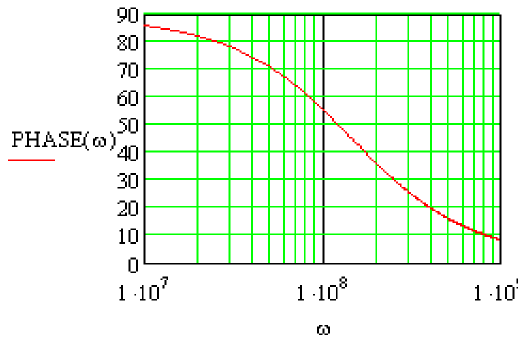


Fig. 4: Transfer function without taking into account input capacitance

Here we see monotonic curve of the amplitude of the transverse function; the phase do not change sign.

The equation for the transfer function written above can be re-written as two independent equations for the amplitude and the phase of this function. Hence, after measuring amplitude and phase of the transverse function for an unknown material at several frequencies in the range of interest (0.1 MHz – 20 MHz), we can find unknown values of L and R2 by solving a system of two equations describing the amplitude and the phase of the transfer function as a function of L and R2. This is convenient to make in the MathCad environment. Knowing the inductance and geometry of the ferrite core, we can calculate permeability of the material at any frequency and its loss tangent.

II. Measurement data

Following this methodic, several materials were investigated with the goal to find the one most suitable for using in the transmission line-type kicker design.

1. G4 Ferrite

Table 1 summarizes all the data obtained for G4 material. The data in the columns G4-1 were taken with R1 = 62.75 Ohm. In the column G4-2 are the data taken with R1 = 148 Ohm. In the column G4-3 are the data of the material that was marked as 5005. Because 5005 ferrite should have $\mu = \sim 1500$, this is clearly a different material. As its properties are quite close to that of G4, the material was marked as G4-3.

Table 1: G4 ferrite

	G4-1		G4-2		G4-3	
f (MHz)	μ	tg(δ)	μ	tg(δ)	μ	tg(δ)
0.2	329.70	0.002			336.09	0.008
0.3	326.29	0.048	334.38	0.014	341.62	0.011
0.5	323.73	0.041	328.85	0.031	328.85	0.008
1	310.53	0.006	324.16	0.015	321.18	0.032
2	321.60	0.042	334.81	0.010	321.60	0.042
5	358.66	0.295	383.37	0.262	382.94	0.213
10	275.17	0.806	263.67	0.903	293.06	0.845
20	87.75	2.81	91.58	2.40	42.60	6.71

Corresponding graphs are shown in Fig. 5 and Fig. 6.

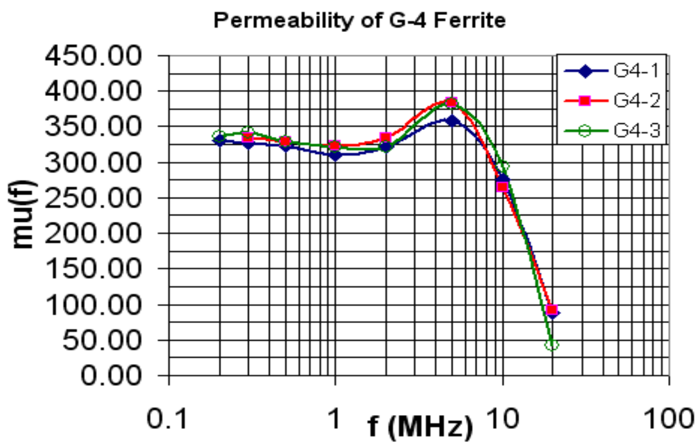


Fig. 5: Permeability of G4 Ferrite

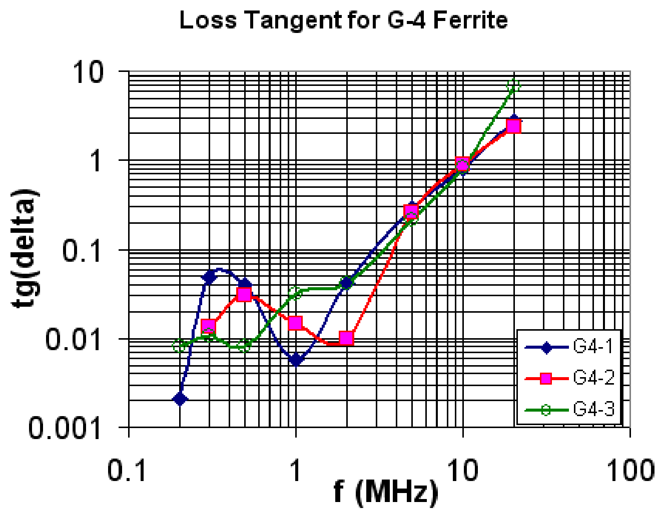


Fig. 6: Loss tangent of G4 material

These graphs can be compared with what the vendor (National Magnetics Group, Inc.) advertises (see Fig. 7).

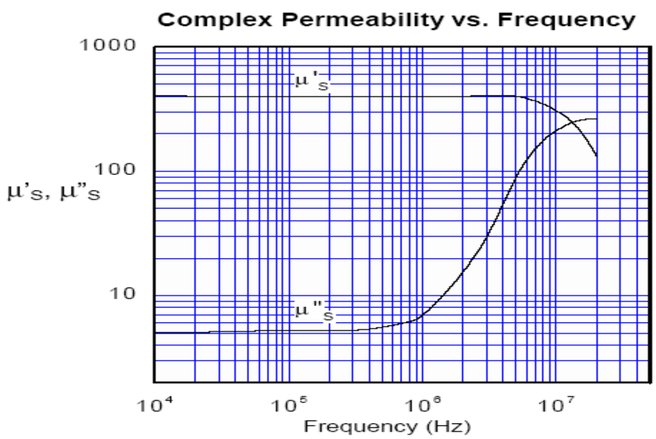


Fig. 7: G4 ferrite properties in accordance with the National Magnetics Group data.

The measured permeability graph is not so flat, and this permeability is definitely lower than μ = 400 we expected in the whole frequency range. The measured cut-off frequency is ~ 13 MHz; the expected value, in accordance with Fig. 7, is ~ 15 MHz.

2. C-2010 Ferrite

Table 2 presents the data obtained using C-2010 material of Ceramic Magnetics, Inc.

Table 2: C-2010 Ferrite

	R = 62.75 Ohm		R = 148 Ohm	
f (MHz)	μ	tg(δ)	μ	tg(δ)
0.2	274.3	0.057		
0.3	288.0	0.020	287.5	0.014
0.5	288.0	0.013	274.7	0.021
1	275.2	0.042	276.9	0.042
2	277.3	0.032	276.5	0.071
5	340.3	0.167	345.0	0.177
10	271.3	0.94	230.0	1.26
20	38.3	7.08	42.6	5.81

Corresponding graphs are shown in Fig. 8 and Fig. 9.

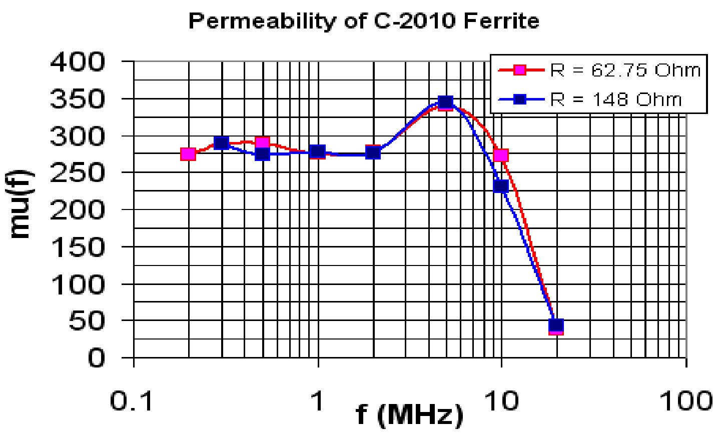


Fig. 8: Permeability of C-2010 material.

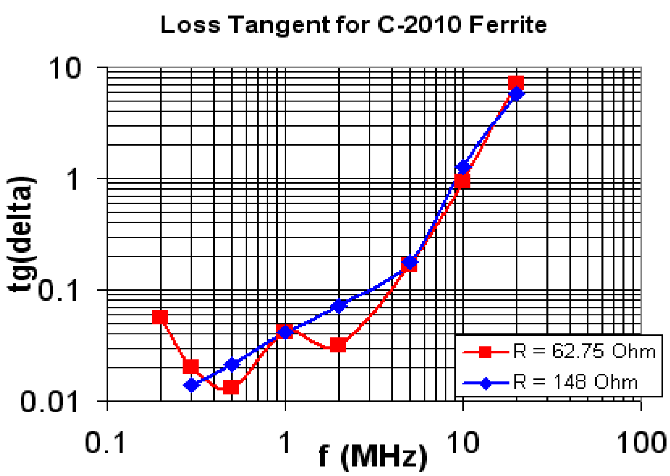


Fig. 9: Loss tangent of C-2010 material.

The vendor's (Ceramic Magnetics, Inc.) data for frequency behavior of the ferrite is shown in Fig. 10.

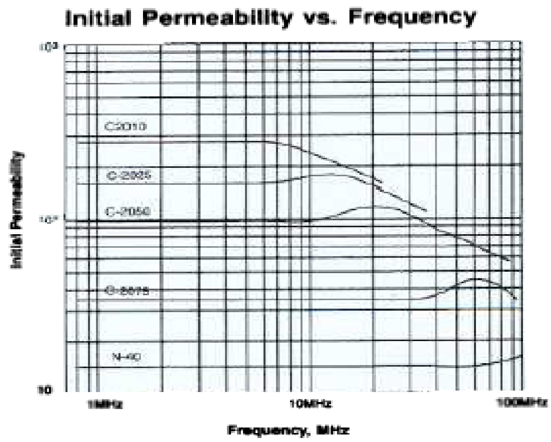


Fig. 10: Ceramic Magnetics data for C20 ferrites.

Below ~ 2 MHz, the measured data is quite consistent with what is expected, but a peak between 2 MHz and 10 MHz is not seen in the vendor's data. Cut-off frequency in Fig. 10 is ~ 30 MHz. Analyzing the measured data, we have it at ~ 13 MHz.

3. C-2075 Ferrite

Finally, there was a ferrite ring marked as C-2075. Table 3 presents the data taken using this ring:

Table 3: C-2075 material

f (MHz)	μ	tg(δ)
1	51.12	0.004
2	49.84	0.012
5	49.84	0.041
10	47.71	0.044
20	64.75	0.052
50	8.52	18.471

Corresponding graphs are in Fig. 11 and Fig. 12.

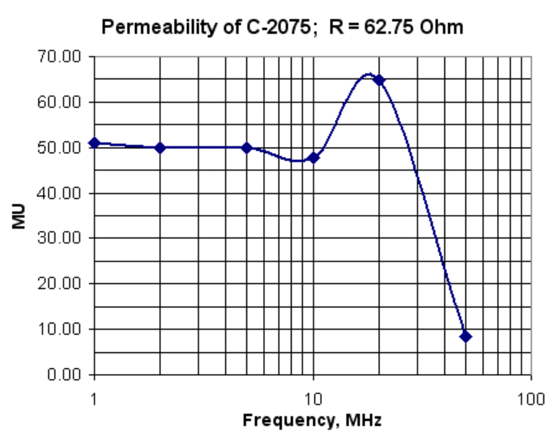


Fig. 11: Permeability of the material marked C-2075.

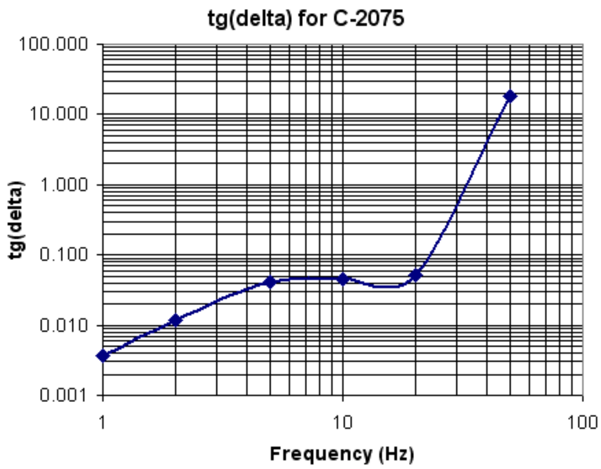


Fig. 12: Loss tangent of C-2075 material

Comparing the data with that in Fig. 10, we see that:

1: The measured low-frequency permeability (~50) is higher than expected (~23);

2. The measured cut-off frequency (~ 40 MHz) is lower that the expected (~ 150 MHz)

According to what was measured, this material should be positioned somewhere between C-2075 and C-2050 in Fig.10

III. Discussion

As we see from Fig. 7 and 10, vendors' permeability data differ from what can be derived from our measurements. For G4 ferrite, the value of low frequency permeability (325) is somewhat lower than the vendor advertises (~400). Frequency range though is quite similar to the published data (~ 15 MHz @ 3 dB). For the 2010 ferrite, the measured low frequency permeability (~ 250) is also a bit lower that the published vendor's data (~ 280). The measured frequency range (~ 13 MHz @ 3 dB) is about what is published (~ 15 MHz). For both materials, the frequency response is not a flat function of frequency; significant increase of the measured permeability can be seen at the upper end of the frequency range with the maximum at ~ 5 MHz. We can suspect some resonance properties of the measurement circuit, but measurement of a different material (C-2075) shows flat behavior around 5 MHz; instead, we see a pick in the transfer function at ~ 20 MHz, which is in a reasonable agreement with the published data. This shows that there are no resonant peak at 5 MHz in out measurement circuit.

REFERENCES:

1. I. Pechenezhskiy, I. Terechkine, "Dielectric Permittivity of Ferrite Samples in the Frequency Range from 0.3 to 20 MHz", FNAL TD note TD-07-014, FNAL, July 2007.